A System-of-Systems Approach Towards Future Space Traffic Management Autonomy and Policy Co-Design

Neera Jain
School of Mechanical Engineering, Purdue University
Mariel Borowitz
Sam Nunn School of International Affairs, Georgia Institute of Technology

1. INTRODUCTION

In the last two decades, there has been significant growth in space exploration worldwide, particularly from commercial entities operating satellite mega constellations or countries that have not historically operated satellites. This growth has been driven in part by humanity's increased reliance on satellite-based services and technologies, including the global positioning system (GPS), satellite imagery, and internet connectivity. Satellite technology enables a myriad of important applications and generates billions in global revenue each year. Growth is especially pronounced in low Earth orbit (LEO), where the rate at which satellites are being launched has increased significantly in recent years from about 1,800 in 2018 to more than 6,700 in 2023 [1] and is expected to continue to accelerate, with more than 60,000 satellites expected to be launched in the next decade [2].

However, space is at risk of becoming a victim of its own success. While new applications and new actors continue to drive growth, near-Earth space remains finite, and Earth's orbit is becoming more crowded. One of the foundational principles of the Outer Space Treaty is "outer space shall be free for exploration and use by all states" [3]. However, ensuring that this remains possible in practice—that new and existing spacecraft can safely operate in Earth orbit—will require concerted effort on the part of individual spacecraft operators and national governments, and must include international coordination. States need to ensure that space does not become so congested that potential new entrants cannot safely engage in space activity, or that existing actors experience collisions that generate debris and further complicate the ability to operate safely in Earth's orbit.

Ensuring the long-term safety and sustainability of outer space requires that spacecraft are able to operate without undue risk of collision with other spacecraft or debris. There are many potential technical and policy solutions for achieving this goal. Minimizing debris in orbit could be achieved by mitigating new debris creation [4] and/or removing existing debris [5]. Avoiding the creation of new debris can be achieved by agreeing to design standards, such as avoiding the use of explosive bolts [6], or implementing more stringent rules related to the deorbit of satellites at the end of their lifespan [7]. Risk of collision between operational spacecraft could be reduced by limiting the number of spacecraft in particular orbits [8] and/or by improving the quality of information regarding the location of objects in space [9]. Developing clear right of way rules for space [10], improving inter-operator communication, and/or enabling automated maneuverability [11] could also improve the safety of space operations.

However, all too often, these potential solutions are being pursued by different communities with little coordination, or co-design, between them and little or no comprehensive study of how various technology and policy solutions may interact dynamically to affect desired outcomes. One exception was presented recently in [12] in which potential collision maneuver guidelines for space traffic management are proposed and evaluated (with respect to metrics such as total Delta-V required) using a high-fidelity simulation environment that included models of the current resident space object catalog and orbital dynamics. The authors show that differences in right of way rules can have significant impacts on the distribution of costs among different types of users.

Sustainable solutions will require multiple policy and technical approaches, with careful consideration of the interconnected nature of the overall environment and the impact that any policy change or technological innovation will have on the overall system. The contribution of this paper is a holistic modeling framework that can be used to predict and analyze the combined effect of technology and policy solutions for the satellite collision avoidance problem in low Earth orbit. Specifically, we show that space traffic management embodies the defining characteristics of a System-of-Systems (SoS)—namely that its constituent elements (individual satellite subsystems, satellites, and satellite constellations) embody *operational and managerial independence* and are *geographically distributed*. Additionally, satellite capabilities and operations, including relevant policies and stakeholders, change over time and thus exhibit *evolutionary development*, and *emergent behavior* can be expected as a result of the interactions between satellites, their operations, and policies.

We apply an established SoS engineering methodology to define STM across two key dimensions. The first involves a set of hierarchical levels that captures how individual systems or entities at the lowest level of the hierarchy are combined to establish systems of systems at superior levels of the hierarchy. This allows us to consider technical and policy solutions that occur anywhere from the satellite subsystem level, such as installation of spacecraft tracking beacons, to system-wide solutions, such as capacity limits for certain orbits or internationally agreed-upon rules of the road. The second dimension focuses on features or considerations of the SoS, categorized in terms of relevant resources, operations, policy, and economics. This ensures that the model developed here explicitly considers not only technical challenges and opportunities, but also those of operations, economics, policy, and international coordination.

We further use the proposed definition to design a conceptual modeling framework for STM that could be used to answer the question "*What combination of policies and collision avoidance technologies will lead to a minimization of collisions in low Earth orbit?*" Although parameterization and implementation of the model is outside the scope of this paper, we discuss the challenges of doing so as well as the opportunities afforded by this approach. Importantly, the proposed SoS definition could help researchers working on individual solutions to better understand how their technology or policy connects to other potential solutions and overall system dynamics. The model definition and framework could also provide a roadmap for other researchers and stakeholders interested in STM to guide their own modeling and analysis efforts aimed at understanding the challenges of STM. Importantly, the SoS engineering-based approach applied here provides a way to bring together many of these concepts to jointly analyze their potential impact on the safety and sustainability of the space environment, while also considering the rapidly changing nature of the space environment itself.

The paper is organized as follows. In Section 2, we introduce the reader to SoS engineering and describe why space traffic management can be characterized as an SoS. In Section 3, we apply a specific SoS engineering methodology to define space traffic management in terms of its resources, operations, policy, and economics. In Section 4 we propose a model abstraction based upon the aforementioned SoS definition and discuss the challenges, opportunities, and implications associated with building and implementing such a model. We conclude the paper with proposed next steps.

2. BACKGROUND

2.1 System of Systems Definitions and Methodologies

The discipline of system of systems engineering (SoSE) has grown out of a need for rigorous tools and methodologies toward analyzing increasingly complex systems across a wide range of sectors. Maier [13] is often credited with defining the most common set of characteristics that describe an SoS: operational independence, managerial independence, geographic distribution, evolutionary development, and emergent behavior. A recent survey summarizes this and other sets of defining characteristics that have been proposed, many of which build on this original set [14]. They all have in common a notion of *emergent behavior*—the idea that interactions among constituent systems yield new or dynamic behavior that cannot be discovered when considering or analyzing one or more subsystems alone.

SoSE methodologies have been used successfully for modeling a wide range of complex systems, such as transportation [15]–[17], the environment [18], and critical infrastructure including utilities [19]. For example, in the context of air transportation, an SoS approach was used to examine how to transform the air transportation system to a state that could satisfy growing demand efficiently by considering two key stakeholders: service providers and infrastructure providers. Model analysis revealed how the desired system-level behavior could be achieved given the individual decisions of airlines (service providers) to grow and restructure routes, conditioned on specific variations in infrastructure made by the FAA and airports (infrastructure providers), and the inherent interactions that would evolve as a consequence [20]. This was possible because the SoS model captured the "competition and cooperation driving the stakeholder behavior" [20]. Similarly, in the context of regional Class 8 truck freight transportation, an SoS approach was used to examine how best to achieve widespread adoption of battery electric powertrains for Class 8 trucks, which can significantly reduce emissions. Researchers found that not only did the payload capacity of Class 8 trucks powered by electric powertrains need to meet that of diesel vehicles, but charging times would need to be less than 2 hours [17], [21]. These types of findings are useful because they can provide guidelines not only for policy makers, but also provide specifications for technology developers as well. Recently, SoSE has been applied to space systems to model an architecture for mitigating space debris [22] and to analyze the impact of autonomy level on spacecraft sizing [23]. However, an SoS approach has not been applied to the space traffic management problem.

Significant research in the SoS field has focused on the tools and methodologies needed for modeling or architecting an SoS [14], [24]. Given our interest in explicitly capturing the interdependence between technology and policy solutions, we apply a well-established modeling and analysis methodology for SoS first proposed in [16] and subsequently applied to several types of SoS. The methodology involves three phases: definition, abstraction, and implementation, or DAI [25]. In the *Definition* phase, the SoS is decomposed across two dimensions. The first is a set of hierarchical levels in which the α-level is considered the lowest, or most granular, level of the SoS, and subsequent levels are systematically comprised of subordinate level entities. The second dimension considers the Resources, Operations, Policies, and Economics (ROPE) associated with each level of the hierarchy. The purpose of the *Abstraction* phase is to build a conceptual model that captures the relationships between constituent elements of the different hierarchical levels and ROPE categories. Finally, the implementation phase is aimed at realizing the conceptual model using parameterized mathematical relationships and computer simulation. This in turn enables analysis aimed at testing specific hypotheses. The scope of this paper is to consider the definition and abstraction phases for developing a Space Traffic Management SoS.

2.2 Space Traffic Management as a System of Systems

Here we adopt Maier's original defining characteristics of an SoS as the basis for verifying that space traffic management can indeed be considered a system-of-systems. These characteristics are summarized in Table 2 for the benefit of the reader.

Table 1: SoS characteristics [13].

Characteristic	Description
Operational independence	SoS elements have their own useful purpose independent of the SoS.
Managerial independence	SoS elements operate independently to achieve a dedicated purpose that is independent of the SoS.
Geographical distribution	Elements are physically distributed with little or no physical interaction but may exchange information or knowledge with one another.
Evolutionary development	The SoS and its constituent elements change in structure, function, or purpose over time
Emergent behavior	Properties of the whole emerge from the assembly and interaction of elements.

For the purposes of this paper, we define the core physical elements of the space traffic management (STM) system to be the individual satellites or satellite constellations operating, or planning to operate, in low Earth orbit (LEO). It should be noted that the restriction to LEO is primarily for clarity of exposition as it aids in developing a concrete SoS definition and model conceptualization. Nonetheless, the scope of the STM problem could readily be expanded in a subsequent analysis. While each satellite or constellation of satellites has its own useful purpose, when considered together, these spacecraft (and the organizations that own and operate them) constitute one interconnected "space traffic" system. Each spacecraft or constellation is operated independently, with a dedicated, independent purpose, such as providing precision location information, collecting imagery of the Earth, or enabling global communication. Even spacecraft that have missions related to space sustainability, such as in-space space surveillance satellites and active debris removal systems, make independent determinations regarding the design and operations of their spacecraft and are subject to the same regulations and norms as other spacecraft. All spacecraft are geographically distributed throughout Earth orbit.

SSA data and service providers, national decision-makers and regulators, and international bodies also contribute to the Space Traffic Management system even though they are not physically present in outer space. These types of operational, economic, and policy contributions are discussed below. Existing space debris is a physical element that affects Space Traffic Management. In our approach, this is considered as part of the space environment as a whole. Additionally, satellite capabilities and operations, including relevant policies and stakeholders, change over time. This, and the addition or removal of satellites from LEO contributes to the *evolutionary development* of the SoS. Finally, *emergent behavior* can be expected as a result of the interactions between operational satellites and associated policies.

3. SYSTEM OF SYSTEMS DEFINITION

As stated earlier, we decompose the SoS across two dimensions: the first is a set of hierarchical levels in which the α-level is considered the lowest, or most granular, level of the SoS, and subsequent levels are systematically comprised of subordinate level entities. The second dimension considers the SoS Resources, Operations, Policy, and Economics (ROPE). For the problem at hand, the hierarchy is defined as shown in Table 2.

Table 2: Hierarchical levels of SoS definition for STM.

Level	Description
Alpha (α)	Satellite subsystems relevant for space traffic management
Beta (β)	Individual satellites within LEO
Gamma (γ)	Groups of satellites within LEO
Delta (δ)	All operational satellites within LEO

3.1 Resources

Resources are defined by DeLaurentis and Crossley as "the entities (systems) that give physical manifestation to the system-of-systems" [15]. Resources are important to define in the SoS because they typically impact the operations that occur across the SoS and consequently, the resultant emergent behavior that designers are interested in predicting. In the context of the hierarchical levels defined in Table 2, we define the resources as shown in Table 3.

Table 3: Resource definition across SoS hierarchy.

Alpha (α)	Beta (β)	Gamma (γ)	Delta (δ)
• Satellite level of autonomy (ground controlled, automated, high-autonomy) • Thrusters (for satellite maneuverability) • Solar power • Fuel (for maneuvering) • On-board sensing technologies (to detect other objects) • On-board communication technologies (intersatellite, broadcast to ground) • Tracking technologies (on board GPS)	• Individual satellite • Ground stations	• Satellite groups – Satellite clusters (< 10) – Constellations – Mega-constellations (>100 satellites)	• All operational satellites

When decomposing this system into hierarchical levels, the α-level, or most granular level of the system, focuses on satellite subsystems. This is important because there are several subsystems within a satellite that owners can incorporate into their design that are relevant for the problem of collision avoidance between operational satellites. This predominantly includes subsystems responsible for maneuvering, sensing, and communication. Within the maneuvering category, we consider the actuation of the satellite in terms of thrusters for station keeping or attitude control. We also consider the power needed for thrusting and supporting auxiliary systems (sensing, communication) as a resource; this includes fuel and/or solar power. Within the sensing category, resources could include the ability to do on-orbit imaging or ranging. Similarly, in the communication category, this could include the ability for intersatellite communication and communication with a ground station.

The β-level consists of resources comprised of α-level entities. In this case, the primary resource at the β-level is an individual satellite. We hypothesize that the decisions of owners and operators regarding these individual satellites and constellations greatly influences the evolution of the system as a whole. We also consider the ground station that the satellite communicates with to be a resource at this level because the number and location of ground stations can affect the accuracy of operators' information regarding the location and health of their own satellite.

At the γ-level, we consider resources comprised of β-level entities. In the current space environment, it is important to consider several resources at this level, all of which represent types of groups of satellites. One resource at the γ-level is a satellite cluster which generally refers to a small group of satellites (e.g. less than 10). This could include, for example, satellites that are closely spaced, operate in nearly identical low Earth orbits, and are typically coordinated in some way (e.g. to conduct a rendezvous and proximity operation). NASA's A-Train, which involves multiple international spacecraft flying in a coordinated orbit that enables data fusion, would fall into this category. Next are satellite constellations, where mega-constellations are generally comprised of hundreds or thousands of satellites that operate in a coordinated manner. Mega-constellations have been developed for communications, Earth observation, and other applications. At the δ-level, the resources are defined as all operational satellites.

3.2 Operations

Operations are defined as "the application of intent to direct the activity of physical and non-physical entities" [15]. For our purposes, this includes the choices individuals or organizations make regarding how to operate their spacecraft. For the SoS hierarchy of interest, the operations at each level are defined in Table 4.

Table 4: Operations definition across SoS hierarchy.

Alpha (α)	Beta (β)	Gamma (γ)	Delta (δ)
None	• Satellite launch • Station-keeping • Service-specific operations (e.g. data collection) • Communication with ground station • Accessing or responding to National SSA network (varying accuracy, precision, availability)	• Clusters − Intra-cluster coordination • Constellations − Satellite replenishment − Intra-constellation collision avoidance − Station-keeping • Accessing or responding to national SSA network (varying accuracy, precision, availability)	• Collision avoidance • Accessing or responding to global SSA network (varying accuracy, precision, availability)

At the α-level we do not define any operations that are relevant to the scope of collision avoidance between operational satellites. Instead, operations become more relevant at the β-, γ-, and δ-levels. At the β-level which is comprised of individual satellites, operations include station-keeping, and additional operations, including maneuvers, that are specific to the aim or function of the satellite. An example of the latter is a satellite maneuver to adjust its position in order to capture specific images. At the γ-level, there are satellite group and constellation-specific operations that should be considered, including the replenishing of satellites within the constellation as well as intra-constellation (or cluster) collision avoidance and station-keeping of the aggregate constellation (or cluster). Note that satellite launch at the β-level is included because as the space environment becomes more congested, scheduling of satellite launch may need to be more carefully coordinated across owner/ operators. Finally at the δ-level, we consider collision avoidance within LEO, as well as the launch and removal of satellites to and from LEO, respectively. Moreover, we consider accessing a prospective multilateral or global SSA network to also be a critical operation at this level. While no such system exists as of right now, SSA and STM coordination among nations has been increasing [26], and many believe that close global coordination on SSA and conjunction warnings will be necessary in the future.

3.3 Policies

Here, *Policies* are defined as "the external forcing functions that impact the operation of physical and non-physical entities" [15]. The relevant policies at each level of the SoS hierarchy are presented in Table 5.

Table 5: Policy definition across SoS hierarchy.

Alpha (α)	Beta (β)	Gamma (γ)	Delta (δ)
• Standards for − Thrusters − Embedded autonomous systems − Communication − Sensing • Future regulations/ principles: − Ability to maneuver requirements	• FCC regulations • NOAA regulations • IADC guidelines • Space Sustainability Rating (SSR) • Future regulations/ principles − Standards for quality of ephemeris data − Information sharing requirements − Designation of low Earth orbital zones to manage traffic	• FCC regulations *for constellations* • NOAA regulations *for constellations* • IADC guidelines *for constellations* • Future regulations that are constellation specific	• Right-of-way rules for space traffic • International space laws and treaties • Outer Space Treaty (Article VI) • ITU regulations • IADC guidelines • Future regulations

Policies at the α-level are those that would affect the design of the satellite and the choice of sub-systems for the satellite. These could include regulations that require spacecraft to be maneuverable (at least under certain conditions), policies that require the ability to carry out automated information exchange or maneuver, a requirement to include beacons or automated identification systems, or other capabilities. β-level policies focus primarily on the operations of spacecraft. This includes existing legislation, like the requirements associated with obtaining an FCC (Federal Communications Commission) license, an FAA (Federal Aviation Administration) launch license, and a NOAA (National Oceanic and Atmospheric Administration) Commercial Remote Sensing license in the United States. Internationally, debris mitigation guidelines, such as those developed by the Inter-Agency Space Debris Coordination Committee (IADC), would operate at this level. Non-binding principles or norms could apply at this level, as well. For example, the Space Sustainability Rating offers an optional way for spacecraft operators to demonstrate that they are taking steps to contribute to space sustainability beyond the requirements of existing legislation [27]. Future regulations or principles could include data sharing requirements, data quality standards, requirements to maneuver in particular cases, or the designation of specific orbital zones within LEO to manage space traffic. At the gamma level, we include regulations and principles aimed specifically at constellation operators. While these types of regulations and norms are only beginning to be developed, they may become increasingly important in the future.

Finally, at the δ-level, we consider policies and norms that would apply at the international level and that govern the interactions among all satellites in LEO. Existing space treaties fall into this category. However, while these treaties lay out important principles, such as the concept of space remaining free for use by all, as well as the requirement for nations to provide authorization and continuing supervision of non-state actors within their nation, they offer little operational guidance for space traffic management [28]. The International Telecommunication Union (ITU) regulations traditionally deal with spectrum allocation and assignments of orbital slots in geostationary equatorial orbit (GEO), but efforts to address these issues are increasingly interacting with larger concerns regarding crowding in low Earth orbit, and some believe the ITU should expand its remit to more directly address space sustainability issues [29]. Future international agreements (binding or non-binding) regarding right of way rules for space traffic would also apply at this level.

3.4 Economics

The fourth dimension, *Economics*, is defined here as "the non-physical entities…that give intent to the SoS operation" [16]. The relevant economic considerations at each level of the SoS hierarchy are presented in Table 6. At the α-level this includes the capital cost associated with the specific technologies defined as *Resources* at this level. For example, the relative cost of different thruster technologies would be evaluated by a satellite owner/ operator when building the satellite. At the β- and γ-levels, several more factors affect the economic considerations of satellite owner/operators. At both levels, the cost of the satellite or satellites (in the case of a cluster or constellation) are defined; these include launch and fuel costs, as well as insurance. At both levels, the cost of SSA services must be considered. A more difficult cost to quantify, at either level, is the cost to the owner/ operator's *reputation* of a collision-related disruption in services or involvement in a debris-creating event. Finally the economics definition also includes the profit or value associated with the services to be provided. At the δ-level, we define costs that arise from the interaction of satellites across LEO. These include the cost, both to individual satellite owner/ operators and the broader space community, of debris that would result from a collision, the cost of international tensions driven by conjunction or collision-related incidents, or even loss of human life.

Table 6: Economics definition across SoS hierarchy.

Alpha (α)	**Beta (β)**	**Gamma (γ)**	**Delta (δ)**
• Capital cost of technologies designated as *Resources*	• Cost of satellite (including launch, fuel, insurance) • Cost of human operators • Cost of SSA services • Cost of ground station • Profit (value) associated with services provided by satellite • Reputational costs associated with individual satellite operation	• Cost of satellites (including launch, fuel, insurance) • Cost of human operators • Cost of SSA services • Cost of ground station • Cost of replenishing satellites in a constellation • Profit (value) associated with services provided by satellite (if applicable) • Reputational costs associated with constellation-level operation	• Cost associated with debris that would result from a collision • Loss of human life (danger to humans) • International tensions (driven by incidents) • Reputational costs associated with interactions between any operational satellites or owner/operators (including nations)

4. SYSTEM OF SYSTEMS ABSTRACTION

Based on the SoS definition presented in Section 3, there are several ways in which a model could be conceptualized or abstracted, depending on the core research question of interest. Here, we pose the following research question: *What combination of policies and collision avoidance technologies will lead to a minimization of collisions in LEO?* To propose a modeling framework that answers this question, we consider the perspective of the satellite owner/ operator whose decision-making is independent from that of other owner/ operators but influences the shared LEO space environment as well as global SSA services. The abstraction phase of the Definition-Abstraction-Implementation SoSE methodology requires that the SoS first be decomposed into sub-domains which then aids in the identification of the sub-models, variables, and parameters that are needed to characterize these sub-domains at an appropriate level of abstraction. A key benefit of conceptualizing the model in this way is that it becomes apparent to the designer how variables within different sub-domains are connected and in turn, drive interdependent behaviors across the SoS.

4.1 Model Abstraction

For the research question under consideration, we define five sub-domains as shown in Figure 1. They are connected in a closed-loop to simulate how the decisions of satellite owner/ operators—to purchase specific types of technologies that impact collision avoidance capabilities—ultimately affect the number of collisions between operational satellites in LEO and the amount of fuel operators must expend to avoid collisions. Two of the five sub-domains are defined as *sub-models* (green shaded rectangles in Figure 1) that represent mathematical descriptions relating one or more inputs and outputs. Three of the five sub-domains are described as *parameterizations* (blue shaded rectangles in Figure 1) as they represent the definition of parameters that must be prescribed or specified to simulate the proposed models.

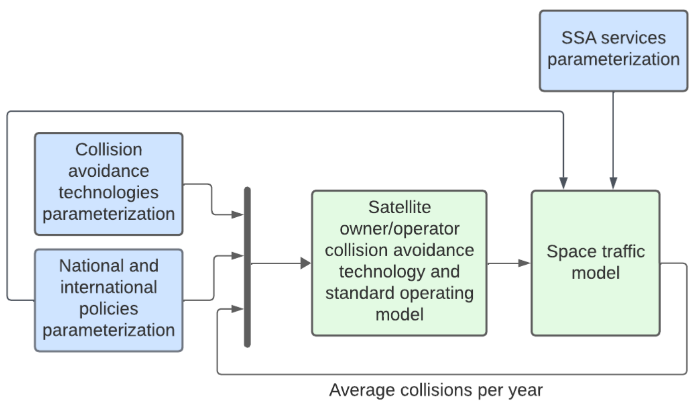

Figure 1: A modeling framework for collision avoidance between operational satellites decomposed into five interconnected sub-domains.

To better describe the modeling framework, a more granular view is provided in Figure 2. We propose that to model owner/ operator technology selection, we consider four categories of satellite owner/ operators: *civil government*, *military*, *commercial*, and *academic*. The underlying assumption is that within each of these categories, there is a representative cost function that could be defined to model owner/ operator collision avoidance technology selection and choice of standard operating procedures[1]. Such a cost function would be defined as a function of the *Economics* variables defined in Table 6, particularly at the α-, β-, and γ-levels, and the *Resources* available at the α-level as listed in Table 3.

Together, the technology selections of the owner/ operators, along with their standard operating procedures, would be used to predict spacecraft dynamics in LEO where all of the individual decisions come together to contribute to the

[1] A similar approach was used to model Class 8 truck fleet heterogeneity across the U.S. line-haul freight transportation system in [17]; in particular it was shown that 12 representative fleets belonging to 3 categories (small, medium, and large fleet) could be used to predict historical adoption of truck technologies.

aggregate space traffic model. Space traffic is also affected by the provision of SSA services, and owner/ operators' responses to these data and services, specifically with regard to whether or not to carry out a collision avoidance maneuver. Ultimately, these decisions will determine how many collisions occur and how much fuel owner/ operators expend in a given time period. This information—number of collisions and fuel expended—will feed back into the cost model that describes how each type of owner/ operator evaluates several different factors (each parameterized appropriately for each owner/ operator type). This allows operators to update their decision-making with regard to satellite design and operating procedures over time, as constellations are refreshed and new systems are developed and launched.

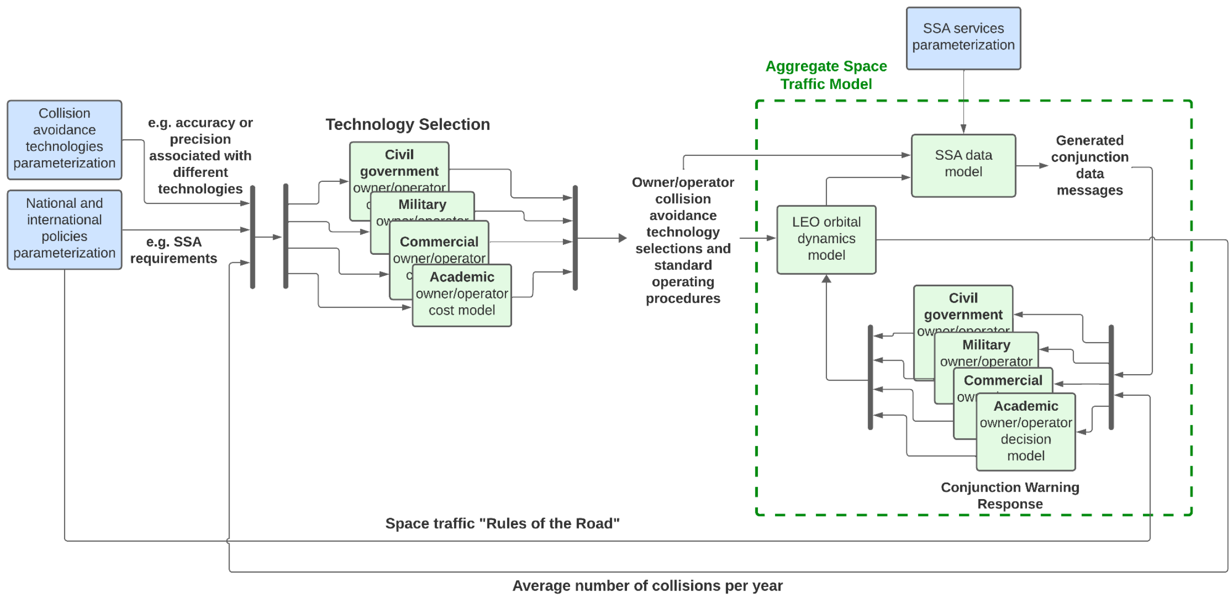

Figure 2: Detailed modeling framework for collision avoidance between operational satellites.

It is worth noting that the SSA services available within the system are informed by the LEO orbital dynamics, a parameterization that represents the capabilities of SSA services providers (government and commercial), as well as the technology selections of the owner/ operators. This allows the model to take into account the way that some technologies—like onboard GPS trackers or laser retroreflectors—could affect the precision and accuracy of SSA services. Similarly, policies that require operators to share ephemeris data, for example, could also impact the quality of SSA services.

A key feature of this model abstraction is the parameterization of U.S. and international policies, based upon the definition provided in Table 5. The model can also accept, as inputs, new technologies that may be available (at different costs) as well as new policies that could be put in place. For example, requirements on the ability to maneuver, which currently do not exist, could be studied in the context of this model. Another feature of this model is the use of cost minimization to predict owner/ operator decision-making. It has been shown that predicting users' behavior by modeling and optimizing their value function, rather than explicitly assuming a particular behavior under a particular condition, can yield better predictions of complex decision-making [17], [21].

4.2 Challenges and Opportunities

Of course, developing and implementing a model based upon the proposed conceptualization shown in Figure 2 will require significant effort to gather relevant data and information. For example, with regard to owner/ operator decisions about technology selections and development of standard operating procedures, information on the cost and performance of various subsystems—including different types of thruster systems, sensors, or on-board tracking devices—is needed. While some spacecraft owners develop their systems in-house or purchase a complete satellite system, there are a growing number of entities that specialize in the sale of satellite components. Data from these providers, along with interviews with spacecraft manufacturers, can help provide the necessary data. It would also be wise to consider systems and components that have been proposed, but may not yet be available on the market. This information, including the relative trade-offs among systems, would also be informed by interviews with spacecraft owner/ operators.

It will also be necessary to work closely with satellite owner/ operators from all four user-types—civil government, military, commercial, and academic—to better understand how they make decisions with regard to collision avoidance. While some work on best practices has been done [30], there is no rule or widely agreed-upon norm guiding these decisions. Some operators, such as those with high risk tolerance, or limited ability to maneuver, may rarely, if ever, respond to a conjunction warning. Others, such as experienced civil space agencies operating large, advanced space systems, may have a team of people reviewing each conjunction warning and gathering supplemental information to plan collision avoidance maneuvers. Modeling the current state of SSA data and services provision, as well as possible future developments, will also require significant data collection and/or estimation. While some SSA providers provide information on their capabilities and the precision and accuracy of their data, detailed information of this type is not typically publicly available. However, a simulation environment can enable analysis of a range of assumptions regarding these parameters.

Finally, as noted above, a key feature of this model is the ability to include the impact of existing and prospective policies on the national and international level. To do this, we will take stock of relevant regulations and requirements that affect the design and operation of satellites, once again verifying these understandings with government representatives, policy experts, and owner/ operators. For prospective policies, it will be important to consider not just the primary impact of these policies, but also potential secondary effects. For example, a rule requiring that all satellites are maneuverable could decrease the number of small satellites placed in orbit, as some prospective satellite owner/ operators (e.g., universities) may find that the added cost and complexity makes their projects infeasible. Alternatively, having a greater percentage of satellites in orbit be maneuverable may reduce predictability and complicate SSA efforts, as it creates a more dynamic environment overall.

5. CONCLUSIONS AND FUTURE WORK

Ensuring the sustainability of outer space requires that spacecraft are able to operate without undue risk of collision, and while there are many potential technical and policy solutions for achieving this goal, tools to effectively design and evaluate these solutions are needed. In this paper we presented a holistic modeling framework that can be used to capture the complexity of the space traffic management problem at an appropriate level of fidelity to begin solution ideation and evaluation. Our approach is grounded in a system-of-systems engineering methodology and explicitly considers relevant resources, operations, policy, and economics that affect the interdependencies of individual satellite owner/ operator decision-making and operation in the shared space environment. While significant, the data collection and modeling challenges posed by this effort are not insurmountable. This modeling approach also offers the opportunity to begin with relatively simplistic representations of systems and decision-making and to iteratively add complexity and realism as additional data becomes available, or interviews reveal deeper understanding of decision-making. Ultimately, the ability to demonstrate and study the interconnected nature of the space traffic management system will be a great improvement over the stove-piped examination of technologies and policies that is possible today.

6. ACKNOWLEDGEMENTS

This project was supported in part by an appointment to the NRC Research Associateship Program at the Air Force Research Laboratory (AFRL) administered by the Fellowships Office of the National Academies of Sciences, Engineering, and Medicine. This work likewise benefitted from several informal discussions with researchers in the Space Vehicles Directorate at AFRL.

7. REFERENCES

[1] "UCS Satellite Database," *Union of Concerned Scientists*. https://www.ucsusa.org/resources/satellite-database (accessed Aug. 31, 2023).

[2] K. L. Howard and A. Von Ah, "Large Constellations of Satellites: Mitigating Environmental and Other Effects," United States Government Accountability Office, Technology Assessment, Sep. 2022. [Online]. Available: https://www.gao.gov/assets/gao-22-105166.pdf

[3] "The Outer Space Treaty," *United Nations: Office for Outer Space Affairs*. https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html (accessed Aug. 31, 2023).
[4] M. K. Macauley, "The economics of space debris: Estimating the costs and benefits of debris mitigation," *Acta Astronautica*, vol. 115, pp. 160–164, Oct. 2015, doi: 10.1016/j.actaastro.2015.05.006.
[5] J.-C. Liou, N. L. Johnson, and N. M. Hill, "Controlling the growth of future LEO debris populations with active debris removal," *Acta Astronautica*, vol. 66, no. 5, pp. 648–653, Mar. 2010, doi: 10.1016/j.actaastro.2009.08.005.
[6] M. Yakovlev, "The "IADC Space Debris Mitigation Guidelines" and Supporting Documents," in *Proceedings of the Fourth European Conference on Space Debris*, Darmstadt, Germany, Apr. 2005.
[7] C. Leck and Q. Verspieren, "Providing for the Safety and Sustainability of Space Activities: The Deorbiting of Defunct Space Objects," *RSIS Commentary*, no. 45, Mar. 27, 2023.
[8] A. Rao, M. G. Burgess, and D. Kaffine, "Orbital-use fees could more than quadruple the value of the space industry," *Proceedings of the National Academy of Sciences*, vol. 117, no. 23, pp. 12756–12762, Jun. 2020, doi: 10.1073/pnas.1921260117.
[9] D. L. Oltrogge and S. Alfano, "The technical challenges of better Space Situational Awareness and Space Traffic Management," *Journal of Space Safety Engineering*, vol. 6, no. 2, pp. 72–79, Jun. 2019, doi: 10.1016/j.jsse.2019.05.004.
[10] H. O. Frandsen, "Towards Right-of-Way Rules in Orbit: Principles & Parameters for Sustainable Space Traffic," *Air and Space Law*, vol. 48, no. 3, Jun. 2023, Accessed: Aug. 31, 2023. [Online]. Available: https://kluwerlawonline.com/api/Product/CitationPDFURL?file=Journals\AILA\AILA2023042.pdf
[11] A. N. Bikos and S. A. P. Kumar, "Enhancing Space Security Utilizing the Blockchain: Current Status and Future Directions," in *2022 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE)*, Oct. 2022, pp. 77–82. doi: 10.1109/WiSEE49342.2022.9926843.
[12] M. Borowitz, B. C. Gunter, M. Birch, and R. J. Macke, "An investigation into potential collision maneuver guidelines for future Space Traffic Management," presented at the Advanced Maui Optical and Space Surveillance Technologies Conference, Maui, HI, 2021.
[13] M. W. Maier, "Architecting principles for systems-of-systems," *Systems Engineering*, vol. 1, no. 4, pp. 267–284, 1998.
[14] C. B. Nielsen, P. G. Larsen, J. Fitzgerald, J. Woodcock, and J. Peleska, "Systems of Systems Engineering: Basic Concepts, Model-Based Techniques, and Research Directions," *ACM Comput. Surv.*, vol. 48, no. 2, p. 18:1-18:41, Sep. 2015, doi: 10.1145/2794381.
[15] D. A. DeLaurentis and W. A. Crossley, "A Taxonomy-based Perspective for Systems of Systems Design Methods," in *2005 IEEE International Conference on Systems, Man and Cybernetics*, Waikoloa, HI, USA: IEEE, 2005, pp. 86–91. doi: 10.1109/ICSMC.2005.1571126.
[16] D. DeLaurentis, "Understanding Transportation as a System-of-Systems Design Problem," in *Proceedings of the 43rd AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada, Jan. 2005.
[17] A. Guerrero de la Peña *et al.*, "Projecting line-haul truck technology adoption: How heterogeneity among fleets impacts system-wide adoption," *Transportation Research Part E: Logistics and Transportation Review*, vol. 124, pp. 108–127, Apr. 2019, doi: 10.1016/j.tre.2018.12.017.
[18] T. Iwanaga *et al.*, "Socio-technical scales in socio-environmental modeling: Managing a system-of-systems modeling approach," *Environmental Modelling & Software*, vol. 135, p. 104885, Jan. 2021, doi: 10.1016/j.envsoft.2020.104885.
[19] I. Eusgeld, C. Nan, and S. Dietz, "'System-of-systems' approach for interdependent critical infrastructures," *Reliability Engineering & System Safety*, vol. 96, no. 6, pp. 679–686, Jun. 2011, doi: 10.1016/j.ress.2010.12.010.
[20] D. A. DeLaurentis, W. A. Crossley, and M. Mane, "Taxonomy to Guide Systems-of-Systems Decision-Making in Air Transportation Problems," *Journal of Aircraft*, vol. 48, no. 3, pp. 760–770, May 2011, doi: 10.2514/1.C031008.
[21] A. Guerrero de la Peña *et al.*, "Projecting adoption of truck powertrain technologies and CO2 emissions in line-haul networks," *Transportation Research Part D: Transport and Environment*, vol. 84, p. 102354, Jul. 2020, doi: 10.1016/j.trd.2020.102354.
[22] T.-Y. Fung, S. S. Roy, Q. Shi, and D. A. DeLaurentis, "Space Junk Aggregation, Neutralization, In-situ Transformation, and Orbital Recycling," in *2022 17th Annual System of Systems Engineering Conference (SOSE)*, Rochester, NY, USA: IEEE, Jun. 2022, pp. 239–245. doi: 10.1109/SOSE55472.2022.9812659.

[23] C. Guariniello, J. Fitch, D. Carpenter, and D. A. DeLaurentis, "Impact of Level of Autonomy on Space Systems Sizing and System-of-Systems Metrics," in *2022 IEEE Aerospace Conference (AERO)*, Big Sky, MT, USA: IEEE, Mar. 2022, pp. 1–10. doi: 10.1109/AERO53065.2022.9843620.
[24] Z. Fang, "System-of-Systems Architecture Selection: A Survey of Issues, Methods, and Opportunities," *IEEE Systems Journal*, vol. 16, no. 3, pp. 4768–4779, Sep. 2022, doi: 10.1109/JSYST.2021.3119294.
[25] N. Davendralingam, A. Maheshwari, A. Raz, and D. DeLaurentis, *Predictive and Prescriptive Analytics via System of Systems Engineering: Informational Determinants for Enterprise-Level Effectiveness*. 2018.
[26] M. Borowitz, "Strategic Implications of the Proliferation of Space Situational Awareness Technology and Information: Lessons Learned from the Remote Sensing Sector," *Space Policy*, vol. 47, pp. 18–27, Feb. 2019, doi: 10.1016/j.spacepol.2018.05.002.
[27] M. Rathnasabapathy *et al.*, "Space sustainability rating: Designing a composite indicator to incentivise satellite operators to pursue long-term sustainability of the space environment," in *Proceedings of the International Astronautical Congress*, International Astronautical Federation, Jan. 2020. Accessed: Aug. 31, 2023. [Online]. Available: https://dspace.mit.edu/handle/1721.1/131216
[28] M. J. Listner, "Op-ed | A reality check on Article VI and private space activities," *SpaceNews*, Jun. 06, 2017. https://spacenews.com/a-reality-check-on-article-vi-and-private-space-activities/ (accessed Aug. 31, 2023).
[29] V. Glaude and C. Karina, "Synergies for outer space sustainability: Lessons from ITU experiences," *ITU Hub*, Oct. 27, 2022. https://www.itu.int/hub/2022/10/space-sustainability-synergies/ (accessed Aug. 31, 2023).
[30] "Satellite Orbital Safety Best Practices.pdf," American Institute of Aeronautics and Astronautics. Accessed: Aug. 29, 2023. [Online]. Available: https://assets.oneweb.net/s3fs-public/2022-09/Satellite%20Orbital%20Safety%20Best%20Practices.pdf